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REFRIGERATION TECHNOLOGY FOR SUPERCONDUCTORS*

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Summary

In the three general subdivisions of this paper we discuss the helium refrigerator contracts in the past several years, the current refrigerator development projects and comment on the maximum practical efficiency obtainable today.

Introduction

Ten years ago, we prepared a list of operational helium refrigerators (excluding liquefiers).[1] The largest by far was a single 1400 watt unit at Langley Air Force Base. In the last two years, nine large refrigerators and liquefiers have been ordered in the United States; five of those have greater capacity than the Langley unit. Relative to ten years ago, today's refrigerators can be expected to require fewer operators, can be smaller, can be operated at off design conditions and 'appear' to be more reliable. The qualifying word 'appear' must be used since there has been no systematic collection of failure rate data for large helium refrigerators in the past; this deficiency in available data inhibits accurate planning.

Greatly improved helium thermodynamic and transport properties and heat transfer data have contributed to design refinements and there has been progress in component and instrument technology. For example, both oil and gas bearing expansion turbines are now on the market covering a much wider capacity range offering the designer more flexibility.

From our point of view, it is heartening to see the start of planning for refrigeration support move steadily into earlier program stages opening the opportunity for more tradeoffs and a better final design. The character of the current programs has generated demands for higher reliability and the incentive to pay for it. It is imperative that a particle accelerator or power transmission line operate continuously for long periods of time. In recent transmission line and accelerator studies[3-4] much attention has been paid to the reliability of the entire system with back up cooling and/or redundant equipment considered. The need for adequate helium purification for the refrigerator, we believe, has been recognized -- evidence shows that impure working fluid has caused many unscheduled shutdowns in the past and at times the destruction of equipment. Development work is in progress on helium compressors, purification, ejectors, cold expanders and compressors, instrumentation and controls.

Low temperature refrigeration efficiency is continually of interest, particularly in view of today's power cost. Several years ago, data for nearly 150 cryogenic refrigerators and liquefiers showed that efficiency increased with size and that the trend seemed to approach a maximum asymptotically.[5] In the last section of this paper we present a model which shows the maximum efficiency that can be obtained with present component efficiencies.

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Recent Helium Refrigerator Contracts

Since about the beginning of 1975, nine large helium refrigerators or liquefiers have been ordered. Three units have been delivered; the remainder are being fabricated.[6,7] Specifications for refrigerators have become much more sophisticated and the designs more flexible. For example, the request for proposals for the US-USSR superconducting power transmission line exchange program refrigerator specified nine alternate modes of operation including simultaneous liquefaction capacity and combined refrigeration and lead cooling at eight operating points at temperatures of 4.5, 6, 8 and 10 K. In addition, it was required that the equipment fit in a space that is relatively small with low overhead clearance.

The nominal capacities and descriptive information for the nine units are given in Table 1.

Utilizing simple conversions to arrive at equivalent refrigeration capacity for the lead cooling streams and liquefaction rates, the total nominal refrigeration capacity is about 21,800 W. The nine contracts total about $\$6.6 \times 10^6$. Note that in some cases the customers supplied the compressors or other equipment separately and those costs are not included above. Also not included are the costs of buildings, foundations, utilities and land. To help compare these helium refrigerator purchases with other segments of the cryogenic industry, a typical single liquefied natural gas peak-shaving plant will cost about $\$20 \times 10^6$. Obviously more industrial R&D dollars will be directed toward the larger market.

Eight of the nine units in Table 1 have turbine expansion devices, six are gas bearing supported and two use oil bearings. The remaining refrigerator has reciprocating expansion engines. In general, gas bearing turbines are more suitable for lower flow rates and oil bearings are used at higher flow rates. There is an overlap region at some intermediate size and power dissipation where either may be employed. However, we repeat, the designer today at least has some choices; a luxury that did not exist a few years ago.

Five out of the nine refrigerators and liquefiers will have oil flooded screw compressors. The screw compressor is a rotating, positive displacement machine capable of respectable pressure ratios in a single stage. However, for such machines there is no long term history in helium refrigeration service and, at present, screw compressors appear to be less efficient than reciprocating compressors. The high pressure ratio per stage without excessive heating is accomplished by pumping relatively large amounts of cooled oil through the machine along with the gas being compressed. Therein lies a potential problem. For continuous operation without fouling heat exchangers, piping, turbine blading and valves, the helium working fluid must be very pure. Various estimates of the allowable oil impurity fall in 10 to 100 ppb range. While tests show that current oil removal apparatus can achieve those low levels, oil carryover into the cold box would have the following effects: The oil will foul or poison the adsorbers intended to remove water and CO_2 so those constituents may pass on and poison the lower temperature adsorbers intended to remove N_2 and O_2 and so on until the entire purification stream is ineffective. The potential for oil contamination along with all the steps taken to eliminate that possibility simply must be weighed against the advantages of smaller size, lower cost, turndown capability and the probable long life that has already been demonstrated by screw compressors in fluorinated hydrocarbon applications.

In the next few years, these nine new refrigerators and liquefiers should provide quantities of operating data useful for further design refinements.

Recent Research and Development

Assessment Studies

Two contracts from the Energy Research and Development Administration, Office of Conservation were intended to review the state-of-the-art for helium refrigeration systems for superconducting power transmission lines, to determine system optimization criteria and to recommend the research and development necessary to made sure that suitably reliable and efficient refrigeration systems would be ready by the 1990's. The two final reports[8,9] contain a wealth of background information including component availability, cost and performance. Since the end application is for the utility industry, emphasis was placed on reliability. While there are many differences between air separation plants and helium refrigerators, there are many common components-instruments, controls, motors, compressors, cooling towers, expanders, heat exchangers and so on. The presentation of air plant breakdown frequency, the reasons for the outages and the time to repair the various malfunctions given in[9] is very interesting. Roughly half of the outages cited were caused by failures in room temperature equipment-electrical, controls, power interruptions, cooling water failures and motors, etc. Not only must the cryogenic equipment be well designed but the normal support equipment must also be of high quality to assure reliability.

Both reports contain reliability analyses considering various combinations of redundant equipment and alternate cooling sources. The reports agree that the switchover gear for placing backup equipment in service is a critical part of the system. The reports also agree that the lack of failure rate data for large helium refrigerators and liquefiers forces the reliability engineer to make 'best estimates' for many parameters.

The major conclusions and recommendations from the two reports are:

Overall Design. The design of the machinery to be cooled and the refrigerator must be an iterative process to achieve an optimum system.

Compressors. Continue screw compressor development. Develop centrifugal helium compressors.

Heat Exchangers. Improvements will be largely in fabrication techniques.

Contamination. Contamination sensors should be developed for long-term unattended operation since those available now are not suited for such service.

Switchover. Develop suitable switchover mechanisms to assure continuous refrigeration.

Reliability/Maintainability Data Bank. Establish a reliability/maintainability data bank and a continuing data gathering system to supply information needed for cost/reliability engineering.

Compressors

At room temperature and up to the moderate pressures used for helium refrigerators, helium behaves very nearly as an ideal, monatomic gas. The ratio of specific heat at constant pressure to that at constant volume is 1.66 for helium as compared to 1.4 for the diatomic gases such as oxygen, nitrogen and hydrogen. The high specific heat ratio and low molecular weight of helium present two compression problems.

1) The specific heat ratio determines the temperature rise of the gas upon adiabatic compression. The larger the specific heat ratio, the higher the temperature for a given compression ratio. In all compressors, the temperatures must be kept below the oil cracking temperature if lubricated or below material limits in any case. Therefore, the permissible compression ratio per stage for intercooled helium compressors is limited relative to other gases and more stages of compression are required for the same final pressure.

2) Rotating centrifugal compressors for high flow rates are attractive because of demonstrated long service life. In the first order, the pressure ratio obtainable per centrifugal stage is dependent on the molecular weight of the gas. For helium, with molecular weight 4, from 8 to 14 intercooled stages would be required for centrifugal compression from one to 15 atmospheres.

Most helium compressors are converted from air or refrigeration service. Very few compressors have been designed and fabricated especially for helium. To our knowledge, all of those have been small.

Screw Compressors

Screw compressors have only recently been used for helium compression. The advantages already listed are very attractive for refrigerators requiring several hundred horsepower input with the oil injection a possible disadvantage. A 150 horsepower screw compressor at Brookhaven National Laboratory for the Superconducting Power Transmission Project has accumulated about 5000 hours operation to date.[10] Initially the unit was run closed loop to determine the operating characteristics and to test oil contamination detection devices. A few minor problems occurred at start up but since then operation has been trouble free with the last 1000 hours in service on line with refrigerators. Sampling techniques for oil detection are not straightforward and further work is planned.

A similar program is planned at Lawrence Berkeley Laboratory.

Regenerative Compressors

A regenerative compressor is a rotating machine that is capable of higher compression ratio per stage than a centrifugal machine and like the centrifugal can be oil free. Improvements in the aerodynamics and a preliminary design for 1270 kW helium compressor modules has recently been reported by Sixsmith.[11]

Central Liquefier and Satellite Refrigerator

Refrigeration for the Energy Doubler/Saver is provided by a large central liquefier and a series of satellite refrigerators located around the ring.[12] The central liquefier cold box is under construction and foundations for the compressors are in place in the compressor building. The compressors, three 4000 horsepower air compressors, are being refurbished; two are to be converted to helium service, the other will be used for a nitrogen reliquefier. A complete satellite refrigerator has been fabricated and is being tested now.

Ejectors and Cold Compressors

Present design parameters for ISABELLE call for forced convective cooling of the magnets with supercritical pressure helium and inlet temperatures below 4.2 K. The lower temperatures can be produced by a refrigerator in which the low pressure stream is below atmospheric pressure; however, the power requirement and heat exchanger cost are high. Two alternatives are being pursued, figure 1(a) and 1(b). Each provides a means for pumping a bath of helium to 3.5 K or below in which the high pressure refrigerant stream is cooled before entering the magnet string. Each offers better efficiency and lower cost than the subatmospheric refrigerator and the advantage that all subatmospheric piping and vessels can be within the cold box vacuum space. A small prototype cold expander compressor is being constructed under a contract from Brookhaven National Laboratory. The high pressure fluid from the heat load drives an expansion turbine which powers a cold compressor on the same shaft. The compressor pumps the lower bath to 3.5 K and the compressor and expander discharges join. The liquid from the two phase stream is seperated in the upper bath while the vapor returns to the refrigerator. Liquid for the lower bath is supplied from the 4.5 K bath through a valve. The high pressure stream at 6 K is successively cooled in the two liquid-gas heat exchangers before entering the heat load.

The cold compressor-turbine expander is expected to be more efficient than the ejector in figure 1b. However, the ejector, which is a jet pump, has no moving parts. Two ejectors have been used for cooling prototype ISABELLE magnets and recently ejector performance tests were made.[13]

Efficiency

Low temperature refrigerator efficiency is usually expressed as percent Carnot, i.e., the ratio of the reversible work required by a Carnot machine to the work required by the actual machine to produce the same amount of refrigeration while operating between the same temperatures. Although the Carnot work is the correct basis for comparing the efficiencies of various refrigerators and liquefiers, the Carnot cycle is not a useful tool for predicting the maximum efficiency for a refrig-using practical components. We have derived an alternate cycle that permits evaluation of overall refrigerator efficiency using 1) practical mechanical components with variable efficiencies, 2) variable heat exchanger efficiencies, and 3) variable system pressure drops. In the limit, with perfect components and reversible processes, the cycle efficiency is 100 percent Carnot. The efficiencies for the alternate cycle are the maximem attainable for refrigerators using available components.

The cycle, figure 2, has: 1) isothermal compressors, 2) counterflow heat exchangers, 3) an arbitrary number of expanders at intervals in the heat exchanger to adsorb heat exchanger irreversibilities, 4) an isothermal expander as the final expansion stage and 5) ideal gas working fluid. The perfect gas working fluid simplifies the efficiency equations and eliminates the irreversibilities of a real gas working fluid. The isothermal final expander, where the heat load is absorbed, is analogous to constant temperature cooling by evaporating liquid at constant pressure. The proportionality constant C in figure 2 defines heat exchanger temperature differences and pressure drop effects are included by taking all the pressure drop immediately before and after the compressors.

Figure 3 compares the calculated maximum efficiencies to the performance of existing refrigerators and liquefiers. The band of calculated maximum efficiencies, from 37 to 42 percent, reflects the variation in heat exchanger performance over a practical range and pressure drop from 10 to 20 percent of the absolute pressure in the high and low pressure circuits. The state-of-the-art efficiencies used for the other components are: 1) compressor -- 60 percent isothermal, 2) loss absorbing expanders -- 80 percent isentropic, and 3) final expander -- 80 percent isothermal. This analysis shows that the efficiency of large capacity refrigerators and liquefiers is approaching the maximum practical.

Any significant increase in the efficiency of large helium refrigerators using a pure working fluid depends primarily on improvements in compressors and expanders rather than some new thermodynamic cycle arrangement. Since compressors and expanders have a long history of development, efficiencies will probably increase slowly. However, we feel that there is a real potential for making this class of machinery more reliable, easy to repair and most important, more cost effective.

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Table I. Large helium refrigerators and liquefiers ordered since 1975.

Agency	Application	Nominal Capacity	Temperature K	Expander Type	Compressor Type	Liquid Nitrogen Precooling
LASL	Energy Storage	900 W	4.5	Turbine Gas Bearing	Reciprocating	Yes
BNL	SPTL*	600 W plus 1.5 g/s lead cooling	6-8	Turbine (3) Gas Bearing	Screw	No
BNL	HEUB Beam Magnets	700 W	4.5	Reciprocating (2)	Reciprocating	Yes
FERMI	Energy Doubler	1500 W	4.5	Turbine (2) Gas Bearing	Screw	Yes
LBL	ESCAR	1500 W	4.5	Turbine (2) Gas Bearing	Screw	Yes
ORNL	MFE Magnets	1500 W or 900 W	4.5 or 3.5	Turbine (1) Gas Bearing	Screw	Yes
FERMI	Energy Doubler	4500 L/hr		Turbine (3) Oil Bearing	Reciprocating	Yes
ERDA	SPTL Russian Exchange	700 W plus 4 g/s lead cooling	4.5	Turbine (2) Gas Bearing	Screw	Yes
U.S. BUREAU MINES	Bulk Liquefier	500 L/hr		Turbine (2) Oil Bearing	Reciprocating	Yes

* Superconducting power transmission line.

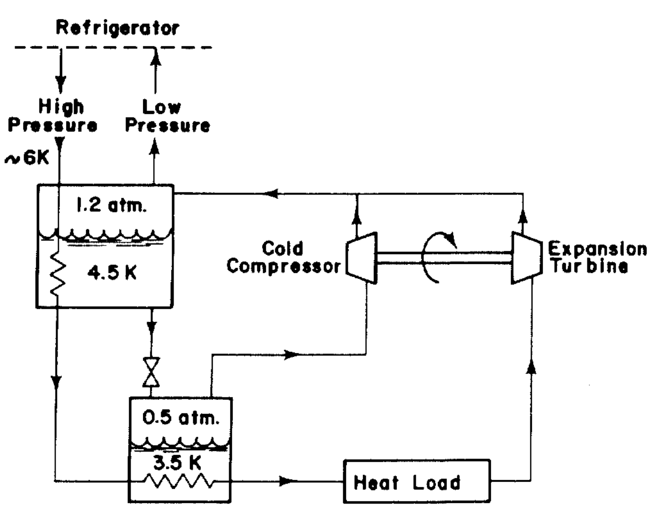

Figure 1(a). Subcooler with cold expander compressor.

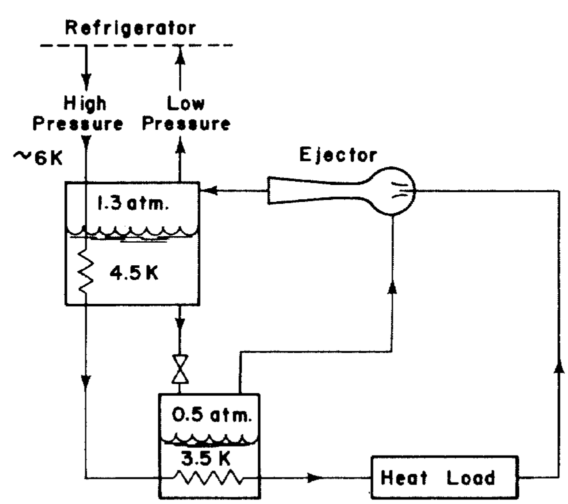

Figure 1(b). Subcooler with ejector.

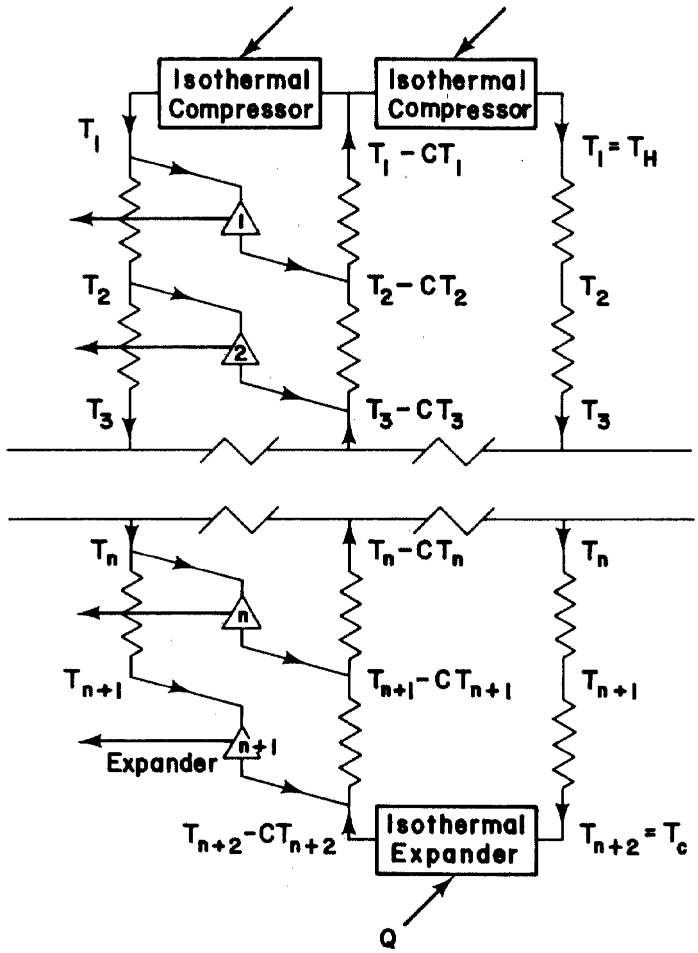

Figure 2. Alternate to Carnot cycle for determining effect of component inefficiencies.

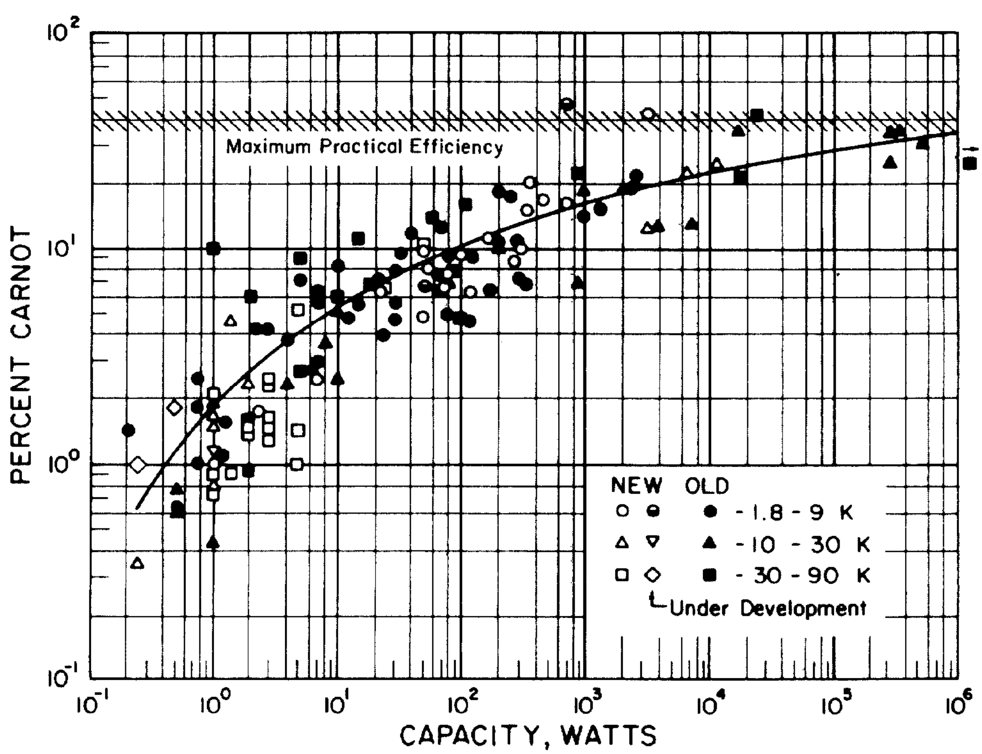

Figure 3. Efficiency of low temperature refrigerator.